City Simulation Software: Perspective of Mobility Modelling

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Abstract — **The field of smart cities and the latest problems in this area of expertise accent the need for interaction among different areas, such as transportation, energy management, education, buildings and others. New technologies and new methods allow for a fast development of each of the areas and of the city itself. At the same time, there is a need for further involvement of citizens and different stakeholders in the decision-making process within cities. In order to demonstrate the impact of a new policy (e.g., building a new shopping center) on certain city aspect (e.g., transportation), simulation models have been recognized as probably the best approach. Unfortunately, there is still no tool that would allow the stakeholders to evaluate the impact of such a policy on a city as a whole and from multiple perspectives. Dedicated simulation frameworks should be used in cooperation, one for transportation, one for energy grid management, another for its impact on the environment until all important aspects are covered. This paper describes a complex tool aiming on overcoming such complicated demands and giving the policy makers one tool to assess impact on different interconnected fields. It combines existing dedicated simulation frameworks into a complete software suite that can combine even contradictory results into one or more performance indicators. This can be used as a decision support system and help in involving citizens into the city government and planning. This article focuses on the utilization of mobility modelling in such a software.**

Index Terms — **Eclipse SUMO, Energy, Environment, Environmental modelling, Integrated Urban Development, Mobility, PALM modelling system, Urbanism, Smart City**

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I. Introduction

In recent years, urban areas across the world are growing, more people are moving into cities, the energy consumption is rapidly increasing, and the world is more and more polluted [1]. A city is a complex system, according to [2]: it consists of several heterogeneous subsystems that interact with each other and through this interaction the overall global behavior emerges. Complex systems self-organize, i.e., autonomously change their behavior or modify their structure, to eliminate or reduce impact of disruptive events.

The research field dealing with so-called smart cities is trying to address the current and future problems of cities. It uses different approaches and concepts and leads to an entire paradigm shift [3]. System scientists have been trying to describe a Smart City system using all sort of analogies, and most of them are right to the point, even if they are different, as there are simply several points of view to consider when describing the city system. Good analogy is with comparing information systems to classical and quantum physics [4], it provides an interesting insight into a certain way of thinking. Then in [5], electrical and mechanical analogies are used to describe the relationship of basic informational quantities. Each ingenious way of thinking of information but also the systems withing Smart City helps define it. We mustn't dwell on one description only. Each point of view provides some fresh ideas.

Major objective of new projects in smart cities must be in improving the quality of life of citizens, especially by providing services (service-oriented architecture). It is important to look at the city and its aspects as a whole and model the synergies among particular city components such as energy, governance, mobility, infrastructure, buildings, healthcare and citizens [6].

From all that was described above, it is clear that the requirements and demand on the policy makers are increasing. They need to involve citizens, look at a city as a whole, and provide services to citizens while sharing resources. This is certainly a challenge. While simulation models are widely used [7] in the particular fields (e.g., transportation, energy management, environmental models and others), there is still no widely accepted and used framework that would assess the impact of certain policy and various aspects simultaneously. It is necessary to involve experts in particular fields and each of them should develop a model for the dedicated area. There is typically no indicator (or a set of indicators) that would take into consideration the interactions among such models. It is

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clear that a certain measure, for example building a new road, can improve the travel times in cities, but at the same time has a negative impact on the (air and noise) pollution of the residential areas it crosses. What improves one field may bring complications to another.

This paper describes the City Simulation Software (CSS), which was created to address such high demands and to fill the existing gap. Its aim is to support the decision-making process. The project team focused on four main topics: Energy, Environment, Mobility (the main focus of this paper) and Urbanism (see Figure 1). To cover all these areas of expertise, a combination of experts from various fields were necessary to properly incorporate the correct point of view in each of the areas. Cooperation of different institutions was the essential aspect of the project. The experts from Faculty of Electrical Engineering (Czech Technical University in Prague, hereinafter referred to as CTU) focused on modeling energy management, Institute of Computer Science of the Czech Academy of Sciences (ICS CAS) focused on modeling environmental aspects, Faculty of Transportation Sciences (CTU) focused on the transportation models and Faculty of Architecture (CTU) on urbanistic models. The CSS software on the top has been developed by experts from the Czech Institute of Informatics, Robotics and Cybernetics (CTU), environmental simulation results presentation and integration modules by the team of ICS CAS.

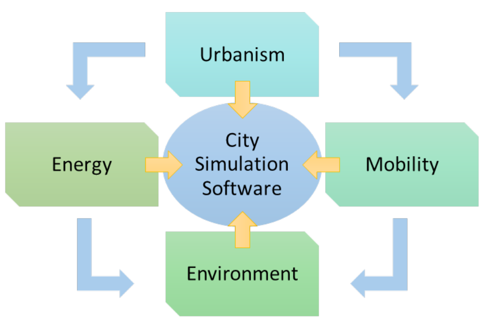

Fig. 1 – Components of City Simulation Software

Energy: The R-Energy smart grid model provides real-time results of water, gas and energy resource – demand model using any possible configuration. It is possible to fully monitor the supply network, efficient distribution of resources in the supply system, match the produced number of resources with the consumed and quickly adapt the network to current events.

Environment: The modelling system PALM has been used to make the environmental model of the selected area. It is an advanced meteorological model system for atmospheric and oceanic boundary-layer flows, originally from 2001 [8], recently published [9,10]. It has been developed as a turbulence-resolving large-eddy simulation (LES) model that is especially designed for performing on massively parallel computer architectures.

Since PALM 5.0, the model contains several components for urban applications, named PALM-4U (PALM for urban applications). Most important modules in PALM-4U for urban application are radiative transfer model (RTM; see[13]) and Building Surface Model (BSM, formerly USM;[11]). Both of these modules have been designed and developed, in cooperation with PALM developers from German Leibniz University Hannover, by a Czech team of ICS CAS [11,12,13].

The results are static or dynamic heatmaps displaying how source transport emissions are affected and formed by the terrain, city thermal convection, vertical shape of landscape, plant canopy, and of course wind and other simulated air flows.

Mobility: the transportation model simulates the traffic environment of a city. Its purpose is to model the behavior of road users in the selected area and provide Key Performance Indicators (KPIs) for individual scenarios. The most efficient way to describe the network of roads is to individually evaluate different segments. The networks can be compared not only by the values of each segment but also by visualizing values in heatmaps. Mobility model is described in more detail in section III.

Urbanism: the model used was the Synthetic Population and Trip Generator model. The synthetic population includes buildings, jobs, visitors, households and demanded trips, but not individuals. It can be used for many purposes. The occupation of buildings can be used to analyze how the amount of people in the area is changing during the day or for energy demand modeling. The trips represent the travel demand, which can be used as input for transportation models.

In Section II, the City Simulation Software will be described – its architecture and functions. Then, a case study from the perspective of the Mobility Model on a pilot area in Prague 6 (Czech Republic) will be described in Section III. Finally, we discuss our conclusion in Section IV.

II. City Simulation Software

A. Architecture

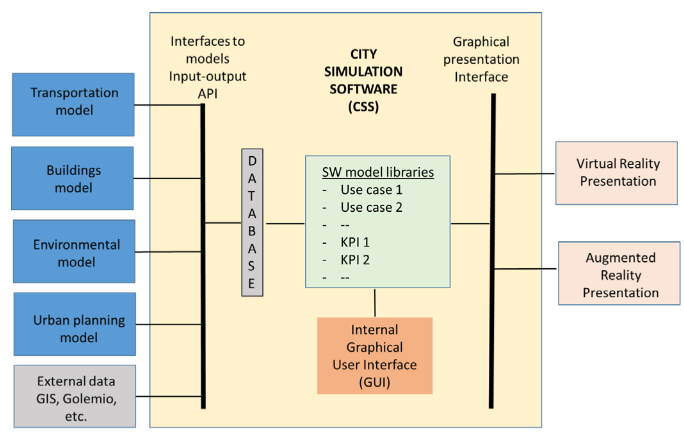

Fig. 2 Architecture of CSS [14]

The city simulation software (CSS) combines existing modeling and simulation tools to make an online model of the entire urban area and provide KPIs in the following sectors: energy, micro-climate and transportation. As seen in Figure 1, an urban planning (urbanism) model is an important source of information for both transportation (mobility) model and

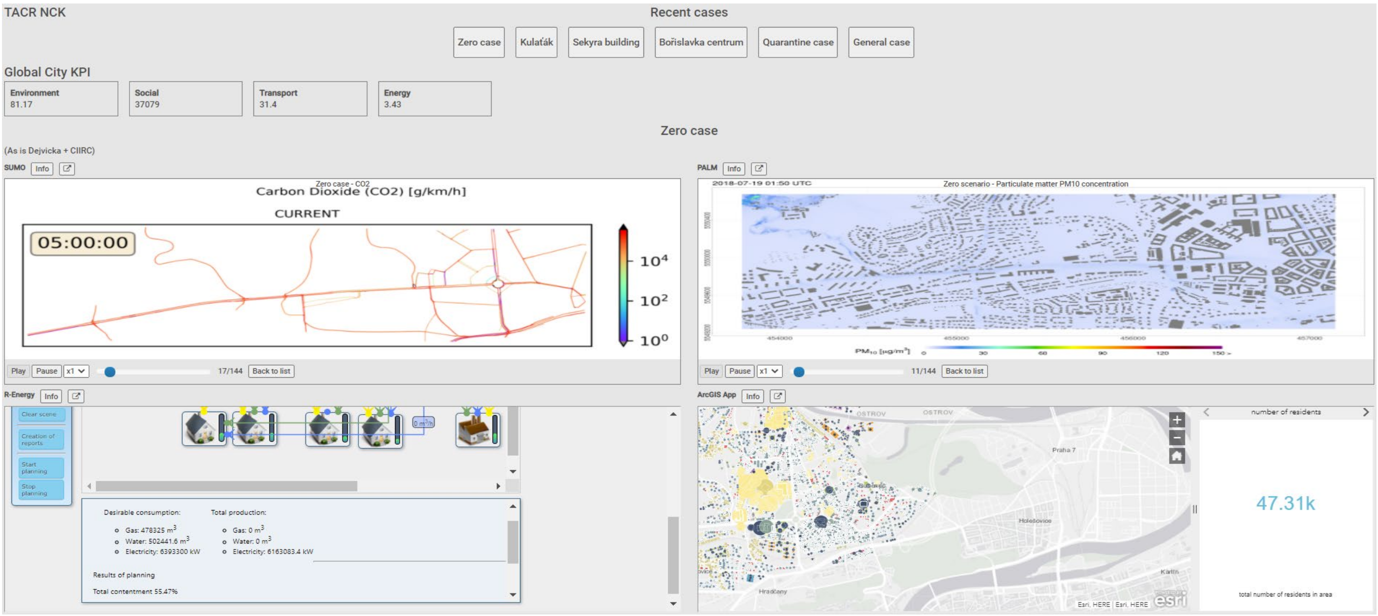

Fig. 3 – Web-based platform of City Simulation Software

building (energy) model, which model dynamic elements and static elements of the area, respectively. Both models will eventually impact the environment, what enables the assessment of sustainability and quality of life. This conceptual architecture can be seen in Figure 2. Examples of KPI are traffic volume, fuel consumption, pollutants PM_x and NO_x [15]. This is because the outputs from the transportation model, i.e., emissions per lane based on traffic flow and fuel consumption, may be directly used as inputs of the environmental model as one of emission sources. From these sources and a 3D model of the buildings as well as topology data from a GIS, the environmental model describes the spread of pollutants and greenhouse gases within the area, contributing to the understanding of the micro-climate in the region and air quality.

B. Functions

III. The main component of the created smart city tool is based on the combination of different microsimulation models for modeling, planning and strategic assessment. The smart city system can be described as connected applications composed of the following elements: tasks (demand), resources (service), data sources (sensor, GPS) and software (platform). To support the structure, all tasks and resources should interact with one another. To achieve that, multiagent technologies were applied.

In multiagent systems, we can organize negotiations among demand agents through different modeling and simulation tools [2]. First, the decision-makers should determine the KPIs for the entire urban area (plan). The agents respectively negotiate with the model to offer to each component the reduced comfort until the desired KPI is reached – the same level of comfort is reached throughout the system and the initial goal (measurable through KPIs) is reached. Each match of demands and resources will have their time slot. If necessary, the plan can be rebuilt in real time, automation makes it resilient [16].

The web-based platform gives an overview of current situation (or "what-if" scenarios) of a part of the city. It uses data from different information sources and simulates evolution strategies of the city. It integrates other existing simulation tools and models to simulate the entire area.

After logging in the CSS, the user can choose a case scenario to evaluate. The system Home page after selection of Zero case scenario can be seen in Figure 3. There is the current case scenario there, Global City KPIs (related to the chosen case scenario) and application panels. There are all four included systems/tools for city simulation and data analysis. Each of the applications is described in the following paragraphs.

The R-Energy smart energy grid model ensures optimal distribution of resources and production plan. It achieves this by making it possible to integrate networks of heat, gas and electricity consumption, and by supporting dynamic schedule resources in real time. It can also make short-term forecasts. In the web application, there is a scheme of a use case. Most of the functions can be found on an extra separate screen (see Figure 3). Users can change suppliers' characteristics, add or remove substation components, specify parameters of the system that consumes energy, add data, set the KPI of the network, define rules of agent's negotiations and generate reports.

The mobility model predicts the influence of major road modification in urban areas and also traffic changes with increasing/decreasing traffic demand related to the city development. It can estimate changes in operational characteristics (such as delay, travel time, speed, traffic flow volumes, etc.) due to the implementation of policies and strategies. Users of the application can choose which of the KPI they want to see, as seen on the top-left side of Figure 3 after selecting the mean traffic flow indicator.

The environmental model gives simulation in a microscale resolution. It combines the solar radiation and the atmospheric phenomena with the objects of the urban area (such as buildings, terrain). The user can pick one of many indicators they want to explore, such as PM_{10}, NO, tropospheric ozone concentration and so on, displayed on the top right hand part of Figure 3.

The synthetic population model includes many population entities, such as residents, households, buildings or land use. It is useful for generating activities of the users of a selected area. The activities can be transport and non-transport. Users can see the following results: modal split, age of residents, trip purpose, number of residents and legend (bottom-right of Figure 3).

The results are shown in two ways: city equalizer (showing various parameters assigned to each smart city; a component in preparation) and a virtual model. By that, an acceptable compromise may be found for the economic, environmental, and social parameters.

IV. Mobility simulation (Case Study)

While the previous sections looked at a city as a whole, this section is devoted to mobility. The integration between PALM model and mobility model has been one of the main aspects of the project. Finding a way to integrate the two environments have been based on emissions. The PALM system can use data from traffic emissions; therefore, the main issue has been to find an efficient way to transfer the data from traffic to environment model. The solution is based on a proper structure of the work from the mobility model, preparing the outputs in such a way, that it can be used by the environmental model.

PALM environmental simulations works with estimation of traffic emissions based on the complete road network of simulation domain of size 3660m x 1440m. Annual emissions totals were based on the traffic census 2016 conducted by the Technical Administration of Roads of the City of Prague – Department of Transportation Engineering (TSK-ÚDI). Emissions itself were prepared by ATEM (Studio of ecological models; http://www.atem.cz) using MEFA 13 model. Emissions from streets not included in the census were available in a grid with 500m spatial resolution. These emissions were distributed between the streets not covered by the census according to their parameters. Particulate matter (PM) emissions included resuspension of dust from the road surface. Time disaggregation was calculated using a Prague 2018 transportation yearbook (TSK-ÚDI [17]) and public bus timetables. This time disaggregation was the same for the primary emissions (exhaust, brake wear etc.) as well as for resuspended dust. Traffic data were supplemented by emissions from other kinds of sources.

Estimated road traffic emissions can be substituted with SUMO simulation results in the case of segments of SUMO simulation road net, which covers only selected important roads, now.

Recently, new services and forms of mobility started to appear within cities, e.g., ride sharing, micro-mobility, and even connected and automated vehicles [18]. New stakeholders are introducing services of shared mobility while others aim to incorporate alternatives for mobility into a large MaaS (Mobility as a Service) ecosystem. The overconnection of these new services and traditional mobility solutions require proper handling of data. Analyzing different data sources with suitable techniques enriches insights into certain mobility solutions. The City Simulation Software (CSS) should be able to not only highlight mobility needs of citizens in a broader context, but also evaluate planned solutions and public policies, in regards to their sustainability as well as the environmental and social behavior impacts while including the necessity of resilience and safety (in the case of mobility, this is mostly road safety and reliability – road safety is currently mostly being addressed through safety inspections and traffic conflict analysis [19,20]).

A. Method

Traffic simulations can replicate the traffic environment and analyze the mobility aspects of an area. In particular, microscopic traffic simulations model the behavior of individual vehicles, considering the interactions between vehicles and other road users, the traffic rules, road design, traffic lights, and other elements.

Eclipse SUMO (Simulation of Urban MObility) [21] is an open source, microscopic and multi-modal traffic simulation software mainly developed by the Institute of Transportation Systems at the DLR (German Aerospace Center) [22]. It simulates how a given group of vehicles and road users moves through a given road network. The system structure of SUMO is based on several input files (in XML format) that describe the configuration and commands to the simulator, and output files that are generated and being written during the simulation. Through TraCI (Traffic Control Interface), an interaction between the simulation in SUMO and Python scripts is possible, which enables the possibility to influence the simulation and get specific information at run-time.

The methodology to set up the simulations in SUMO can be summarized and briefly explained as follows (influenced by the need to balance requirements of the environmental model).

I. Network definition: the initial step consisted of downloading the network data from OSM (OpenStreetMaps) [23] for the simulated area and filtering only selected main roads by expert judgement (see Figure 4 and 5). Manual modifications in the network had to be done so the network model would function properly and match with the real network, this was done via SUMO's Netedit program. The network should fit with PALM's simulation domain for results integration among environmental model input data. The network is by design segmented based on how the network is created.

II. Generation of network additional files: as the majority of the traffic lights in the network were actuated, the location and types of traffic detectors (either induction loops or cameras) were defined according to their current installation. Public transport stops and stations were automatically generated from OSM data.

III. Generation of trips, routes and schedules of public transport: SUMO is able to automatically define PT (public transport) routes from OSM data, though real schedules had to be manually added, when the intervals between vehicles on the same line were not constant. A Python script was created to generate every PT trip from constant and non-constant intervals.

IV. Generation of files to be used as inputs for the generation of trip and routes: a custom vehicle composition (percentages of each type of vehicle) was defined - based on the Czech and Prague's statistics published by Eurostat [24], where vehicle parameters followed SUMO standard values [22], except for pedestrians - in the Czech Republic the walking speed is considered as 1.4 m/s. Then scripts to convert 24-hour travel demands from spreadsheets into SUMO's input format (XML) was coded. This travel demand was initially in AADT (Annual Average Daily Traffic) from [25]. Therefore, it was adjusted into per 10 minutes intervals for a 24-hour simulation based on real measurement of local traffic flow variations.

V. Generation of trips and routes of persons and private vehicles: SUMO has several methods to generate trips, their choice is usually defined by the input data available and the network connectivity type. The team working on the project only had the traffic flow information, which was limited to the roads leading to the roundabout Vítězné náměstí (Victory Square) also known as "Kulat'ák", and there were many entrance and exit points. Therefore, it was decided to measure and calibrate turning rates together with travel demands according to the typical real traffic situation. Pedestrians in our model were included only around the roundabout "Kulat'ák", due to the fact that they have preference over vehicles, which improved the accuracy of the simulation.

VI. Generation of traffic management additional files: at this step the traffic lights plans based on traffic light signal plans provided by TSK were manually set, which followed the timings of real plans in use, except the phase transitions that were simplified. Moreover, to maintain known traffic flow at certain locations the feature in SUMO called calibrators was used. This was done because the network was meshed and turning rates were used. These calibrators inserted or removed vehicles in the simulation to match average hourly flows.

VII. Generation of output additional files: this step was carried out to define which outputs SUMO would have to create for each scenario, such as lane measures and emissions as well as scenario attribute files used either in step VIII and IX.

VIII. Preparation of SUMO configuration file and interaction scripts: the configuration file defined the input files, which were generated in the previous steps, and set other simulation settings. The interaction script was coded in Python, it started and controlled the simulation in some aspects. Due to limited functionality of actuated traffic lights in SUMO, the standard actuated traffic control was unable to work in the presence of transition phases between green phase and multiple alternatives for next phases. One big advantage of SUMO is that by having TraCI able to send commands to the simulation, the Python scripts to mimic the actuated traffic signal plans were created - currently in use in Dejvice. Another standard feature overridden by the team working on the project was the collection of travel times. SUMO measures travel time on roads by the average speed of vehicles, which usually does not reflect the real time vehicles took to traverse the road. To tackle this, each vehicle was monitored, each change of roads was time-stamped, enabling the possibility to measure the real travel times on each road. The last addition was to collect the type, position, angle, and blinker status for every vehicle throughout the whole simulation. The reason for this was to enable plotting the movement of vehicles on the network of the dashboard, instead of the user interface of SUMO.

IX. Start of the experiment: the experiment consisted of doing step V and running the interaction script of step VIII for each scenario repeatedly, in order to replicate the simulation and have a confidence interval for the simulation results.

X. Work with experiment output files: in the last step animated heat maps were created to better visualize how the results were changing throughout the whole simulation time, and comparisons between scenarios were made. The XML files are the fundamental SUMO data file for PALM model integration.

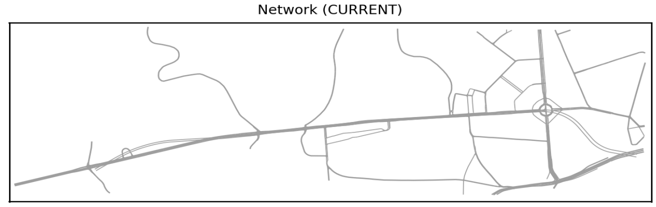

Fig. 4 Road infrastructure for scenarios 1, 3, 4, 5

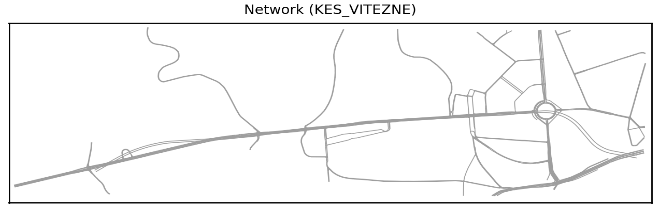

Fig. 5 Road infrastructure for scenarios 2, 6

B. Results

Six different scenarios were examined:

1) Zero case – current (base) state
2) Kulat'ák - after the complete reconstruction of the square Vítězné náměstí and a new transport bypass KES.
3) Sekyra building – two new buildings on the square Vítězné náměstí, new building of CIIRC (already done) and Sekyra building.
4) Bořislavka centrum – new complex of administrative buildings near Bořislavka metro station.
5) Quarantine case – current situation during COVID-19 pandemic
6) General case – combination of cases 2-4 together.

There are three types of results:

A. Heatmaps – heatmaps show the road network with color scale (black are values greater than explicitly stated in scale, e.g., greater than 450 in Fig. 6). Figure 6 shows the mean traffic flow of the network in different scenarios.
B. XML files – containing the value of KPIs (waiting time, speed mean, CO_2, etc.) per each fragment of the network (road sections) per time intervals. Table I presents an excerpt of such XML output file.
C. Spatiotemporal changes of individual vehicles throughout the simulation providing the sheltering SW (CSS) special coordinates in time as well as some additional information such as intention to turn (turning lights), orientation, vehicle type etc.

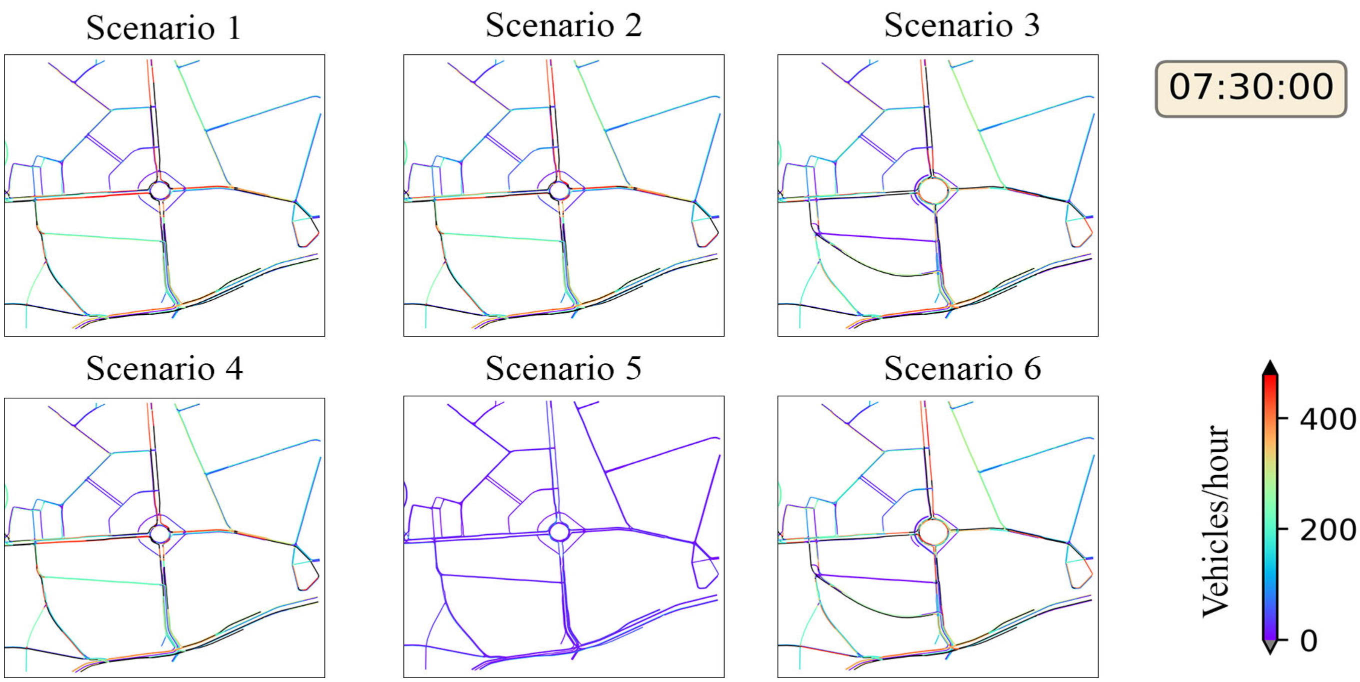

Fig. 6 Traffic flow heat maps for all scenarios at morning peak

The greatest challenge proved to be a simple way to reduce all the information into an easy-to-understand global KPI. However, to get to the global KPI, it is imperative to first understand the informational value of all the different outputs.

While there are tools to measure the overall performance of a transport network or transport system, they are not always easily compatible with other simulation tools (for other areas of expertise). Furthermore, for the purposes of the projects use-case, a microsimulation tool was most suited. Macro simulation tools (e.g., PTV VISUM) are usually used to evaluate vaster areas or entire cities, making it a little simpler to measure overall performance. Therefore, even though micro simulation suits better the needs of the project, it was more difficult to evaluate the entire area with simple numbers. Through the micro simulation, it was possible to measure predetermined KPIs on individual parts of infrastructure (segments of the model) through time. These values were made into a heatmap for an easy visual evaluation of the differences in individual scenarios. For the difference in of used infrastructure see Figures 4 and 5. For scenario comparison, see Figure 6.

Similar to visual comparison through the heatmaps, a more accurate comparison can be made through XML files analysis, where there are exact numbers for individual model segments for each time period. When put together, it could look similar to an example values in Table I. Another way to utilize the detailed values from the whole network would be combination of all KPIs into one number for each segment for each time period through recording how often set limits are breached [8].

The spatiotemporal data are mostly for the purposes of augmented and virtual reality for visualization of what the situation would look like in real life combined with other data from the other models.

Globalization of all the values (every segment, from every time period, from each KPI), however, is a different task. It can be approached similarly to the steps described in [8] and expanded upon. For example, through averages (with the drawback of minimum differences among the scenarios), the averages of just some extreme values, only extreme values etc. The best approach will be one of the main focuses of the continuation of the project.

The need for a globalization of the KPIs is apparent, since the more detailed approach of heatmaps or network values analysis does not provide determinative-enough information for making final decision, as can be seen on figure 6. When combining the data from mobility model with other detailed values from the rest of the models, the need for a more globalized approach is even more apparent.

From the perspective of PALM model, the most difficult feat was to transfer the data from the SUMO outputs. This was resolved by provision of a set of coordinates and identification numbers for different segments for easier integration. The base idea is for the SUMO outputs to serve as inputs for PALM.

TABLE I
EXAMPLE XML RESULTS

From (s)	To (s)	Segment	Scenario	Traffic flow (veh/h)	Delay (s)	…
27,000	27,600	100	1	835	10	
27,000	27,600	100	2	880	12	
27,000	27,600	100	3	875	11	
27,000	27,600	100	4	820	10	
27,000	27,600	100	5	95	1	
27,000	27,600	100	6	840	10	

V. CONCLUSION / DISCUSSION

This paper describes results of a project aiming at developing a tool that combines different areas of expertise and their respective modeling approaches and software. It provides precise and easy-to-read data for decision makers on different development scenarios. It is safe to say that the project was successful in the first steps of a combination/integration of otherwise hard-to-combine areas of expertise in respect to modeling complex changes in the city. However, it is still important to improve the information gathered from all the data from individual models. Simple visualization of all the data will not suffice for all occasions. Simplified information is needed for quick decision with the detailed data acting as a support for detailed analysis of the comparison, if needed. In respect to mobility, the approach presented in [16] will be used and improved upon as mentioned above.

In order to actually combine each different model, it was necessary to develop an integration between the models. The current version of integration is based on utilization of outputs from one model serving as inputs for another model. For instance, the synthetic population provided important data about behavior models for transport modeling and the mobility model provided data for environmental modeling – the traffic emissions used to describe the concentration and transport of pollutants and other emissions into environment of the entire simulation domain.

There are several opportunities for future work. The involvement of multi-agent-based modeling in the project can be extended to react to real-time changes in the system. So far, the mobility part was focused on strategic modification in the long term. While the project can be considered a success in respect to partial integration, there is still an opportunity to make the sharing of data more refined. Regarding transport and environmental modelling, the solution is based in topography, system ontology and the utilization of geospatial data for the outputs. Further investigation should prove beneficial for easier implementation of the described approach. More about the software [26] can be read in [16]. Central point of the effort is also based in proper communication solution that can provide a substantial challenge. More about communication solution in [27].

Acknowledgment

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